Practice Midterm Exam

EES 3310/5310: Global Climate Change

Spring 2020

Instructions

This practice examination has 12 multiple-choice questions, and 5 free-response questions.

On the real test, there will be 8 multiple-choice questions, worth 5 points each and you will have some choice among the free-response questions. Undergraduates will answer 3 out of 5 free-response questions (worth 20 points each) and graduate students will answer 4 out of 5 (worth 15 points each).

The answers are provided at the back of this test, so you can check yourself.

You will have 50 minutes to complete the exam.

Physical Constants

Stefan-Boltzmann constant	$\sigma = 5.67 \times 10^{-8}$ W/m^2 K^4
Average Distance from Earth to sun	1.50×10^8km
Average Distance from Mars to sun	2.28×10^8km
Average Distance from Venus to sun	1.08×10^8km
Radius of Earth	6.4×10^6 m
Solar constant (solar flux at Earth)	$S_0 = 1370$W/m^2
Average albedo of the Earth	$\alpha = 0.3$
Average albedo of Venus	$\alpha = 0.8$
Average albedo of Mars	$\alpha = 0.2$
Greenhouse effect on Venus	510 K
Greenhouse effect on Mars	6 K
Skin temperature of the Earth	$T_{\text{skin}} = 255$K
Average surface temperature of the Earth	$T_s = 288$K
Atmospheric pressure at sea level	$P_0 = 1013$mbar
Dry adiabatic lapse rate	10°C/km
Normal tropospheric environmental lapse rate	6°C/km
Scale height of the atmosphere	$H_0 = 5.6$km
e-folding height of the atmosphere	8km

Equations

Stefan-Boltzmann equation	$I = \sigma T^4$
Wien's law	$\lambda_{\max} = \dfrac{2898\ \mu\text{m/K}}{T}$
Skin temperature	$T_{\text{skin}} = \sqrt[4]{\dfrac{1-\alpha}{4\epsilon\sigma}\, S_0}$, where α is the albedo, σ is the Stefan-Boltzmann constant, ϵ is the emissivity at the skin-level, and S_0 is the solar constant.
Greenhouse effect	$T_{\text{ground}} = T_{\text{skin}} + L h_{\text{skin}}$, where L is the moist adiabatic lapse rate and h_{skin} is the skin height
Temperature conversion:	
Kelvin to Celsius	$T(^{\circ}\text{C}) = T(\text{K}) - 273$
Fahrenheit to Celsius	$T(^{\circ}\text{C}) = \dfrac{T(^{\circ}\text{F}) - 32}{1.8}$
Celsius to Fahrenheit	$T(^{\circ}\text{F}) = 1.8\, T(^{\circ}\text{C}) + 32$
Temperature lapse	$T(h) = T_{\text{ground}} - Lh$, where h is the height above sea level and L is the lapse rate.
Barometric law	$P(h) = P_0 \times 0.5^{h/H_0} = P_0 \times e^{-h/H_e}$, where $P(h)$ is the pressure at height h, P_0 is the pressure at sea level, and H_0 is the scale height of the atmosphere, and H_e is the e-folding height.
Feedback	$\Delta T = -\Delta Q_{\text{forcing}}/f$
Feedback factors	$f = f_0 + f_1 + f_2 + \cdots$, f_0 is Stefan-Boltzmann feedback
Amplification factor	$a = f_0/f$
Calculating fourth roots	The fourth root ($\sqrt[4]{\ }$) is the same as the square root of the square root. On your calculator, it may be easier to push the square-root ($\sqrt{\ }$) key twice than to take the fourth root directly.
Calculating fourth powers	The fourth power is the same as the square of the square. On your calculator, if you have an x^2 key, it may be easier to push x^2 twice than to take the fourth power directly.

Section 1. Multiple-choice questions. Choose the one alternative that best completes the statement or answers the question. Mark your choice on the optical scan sheet.

1. If an external forcing starts to change the earth's temperature, what effect would a negative feedback have on the final temperature?
   - (a) The feedback will make the final temperature even warmer than the forcing alone would have.
   - (b) The feedback will make the final temperature less warm than the forcing alone would have.
   - (c) If the forcing warmed the planet, the feedback would make it even warmer; if the forcing cooled the planet, the feedback would make it even cooler.
   - (d) If the forcing warmed the planet, the feedback would make it less warm; if the forcing cooled the planet, the feedback would make it less cool.
   - (e) None of the above
2. Ocean-floor sediments show a dramatic change at the beginning of the paleocene-eocene thermal maximum. Older sediments are white and rich in chalky carbonate-rich mud. When the Eocene began, the sediments change to red clay. What do we infer from this change?
   - (a) The temperature of the planet suddenly changed.
   - (b) The amount of CO_2 in the atmosphere suddenly changed.
   - (c) The sea level suddenly changed.
   - (d) The conveyor belt suddenly shut off.
   - (e) All of the above.
3. If the sun got brighter and remained that way, which of the following would not happen over the next 1000 years or so?
   - (a) The earth's temperature would rise
   - (b) Water vapor feedback would amplify the effect of the warming sun
   - (c) Silicate weathering would speed up and remove CO_2 from the atmosphere.
   - (d) Cloud feedbacks would increase the albedo enough to cancel out any temperature change and temperatures would remain close to what they are today.
   - (e) neither (c) nor (d) would happen.
4. Which of the following is *not* necessary for a greenhouse effect to occur?
   - (a) The sun's radiative heat has very different wavelengths from the earth's.
   - (b) The atmosphere is transparent to the wavelengths of the sun's radiation.
   - (c) The atmosphere absorbs the wavelengths of the sun's radiation.
   - (d) The atmosphere absorbs the wavelengths of the earth's radiation.
   - (e) Neither (a) nor (c) is necessary for a greenhouse effect.
5. The oceans absorb much more CO_2 from the atmosphere than they otherwise would because the concentration of ________ ions in sea water is much larger than the concentration of dissolved CO_2.
   - (a) carbonate (CO_3^{-2})
   - (b) bicarbonate (HCO_3^-)
   - (c) hydrogen (H^+)
   - (d) all of the above
   - (e) none of the above

6. Where does most of the heat that warms the troposphere come from?
   (a) Absorbing sunlight.
   (b) Absorbing longwave radiation from the earth's surface.
   (c) Absorbing heat from direct contact with the earth's surface, as your hand would warm up when you touch a warm object.
   (d) Chemical reactions in the atmosphere.
   (e) None of the above.
7. What aspect of the Milankovitch (orbital) cycles caused the earth to move into and out of periods of massive glaciation over the course of the last two million years?
   (a) Changes in the global average insolation.
   (b) Changes in the average insolation for the Northern Hemisphere.
   (c) Changes in the summer insolation for high northern latitudes.
   (d) Changes in the winter insolation for high northern latitudes.
   (e) Changes in the length of the seasons.
8. Suppose that a lot of soot were added to the upper atmosphere, and that the soot did not change the earth's albedo but absorbed a lot of the visible light that was not reflected, so it strongly reduced the amount of shortwave light reaching the surface. How would the ground temperature change? (Assume that nothing else changes except the fraction of visible light reaching the surface and that the earth and atmosphere change temperature to balance the heat budget. Specifically, you may ignore feedback effects.)
   (a) It would warm up
   (b) It would cool off
   (c) It would not change
   (d) It could do any of the above, so the temperature would be likely to jump around erratically.
9. How do high and low clouds contribute affect the surface temperature?
   (a) Both high and low clouds warm the surface.
   (b) Both high and low clouds cool the surface.
   (c) High clouds warm the surface and low clouds cool it.
   (d) High clouds cool the surface and low s warm it.
   (e) There is no general rule.
10. Layer models of the atmosphere have no convection. How does convection change the surface temperature from what it would be in a layer model of the greenhouse effect?
    (a) The surface would be warmer with convection than in a layer model.
    (b) The surface would be cooler with convection than in a layer model.
    (c) The surface would be the same with convection as in a layer model.
    (d) The surface could be either warmer or cooler with convection than in a layer model. It depends on the humidity of the air.

11. One layer of sediment from the deep ocean has a higher $\delta^{18}O$ (the ratio of ^{18}O to ^{16}O) than normal sediments do. The most important thing this tells us is that ______ when that layer was deposited.

    (a) the climate was warmer

    (b) the climate was cooler

    (c) the sea level was higher

    (d) the sea level was lower

    (e) None of the above

12. Water vapor is a greenhouse gas just like CO_2. Why do we worry a lot about CO_2 emissions, but not water vapor emissions?

    (a) Because there is already almost as much water vapor as the atmosphere can hold.

    (b) Because water vapor has a very short residence time in the atmosphere.

    (c) Because band saturation means that adding more water vapor will have very little effect on the greenhouse effect.

    (d) (a) and (b)

    (e) All of the above.

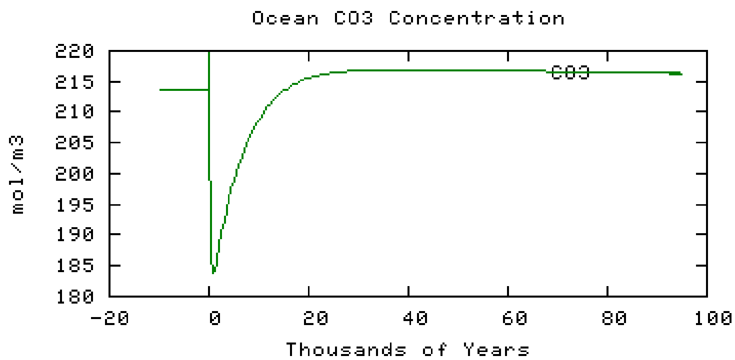
Section 2. Free-response questions (60 points total).

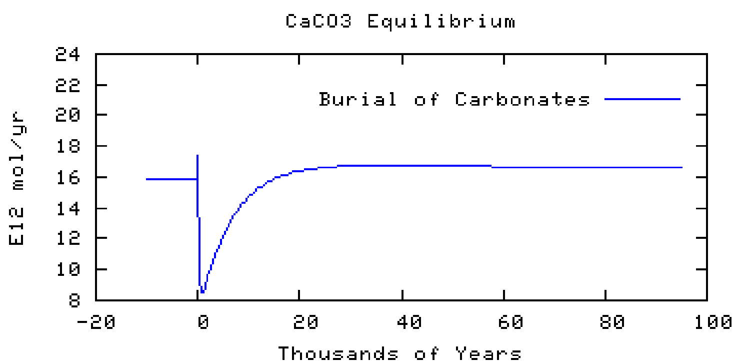
On the real test, you will have some choice in the free response questions. Undergraduates will answer 3 out of 5 questions and graduate students will answer 4 out of 5. Answer questions in the space provided. I have tried to write the questions carefully so you can answer each question, or each part of a multi-part question, in one or two brief sentences.

You **do not** need to fill the page. Lengthy answers are *not* necessary!

1. Consider the ice-albedo feedback:
   (a) How does it work?
   (b) Is it positive or negative?
   (c) Did this feedback play an important role in the Pleistocene ice ages?

2. The figures below show changes in both the concentration of CO_3^{-2} ions in sea water and the rate at which carbonate minerals (mostly shells of tiny plankton organisms) are buried in sediments on the sea floor after a big pulse of CO_2 is released into the atmosphere.





Briefly describe:

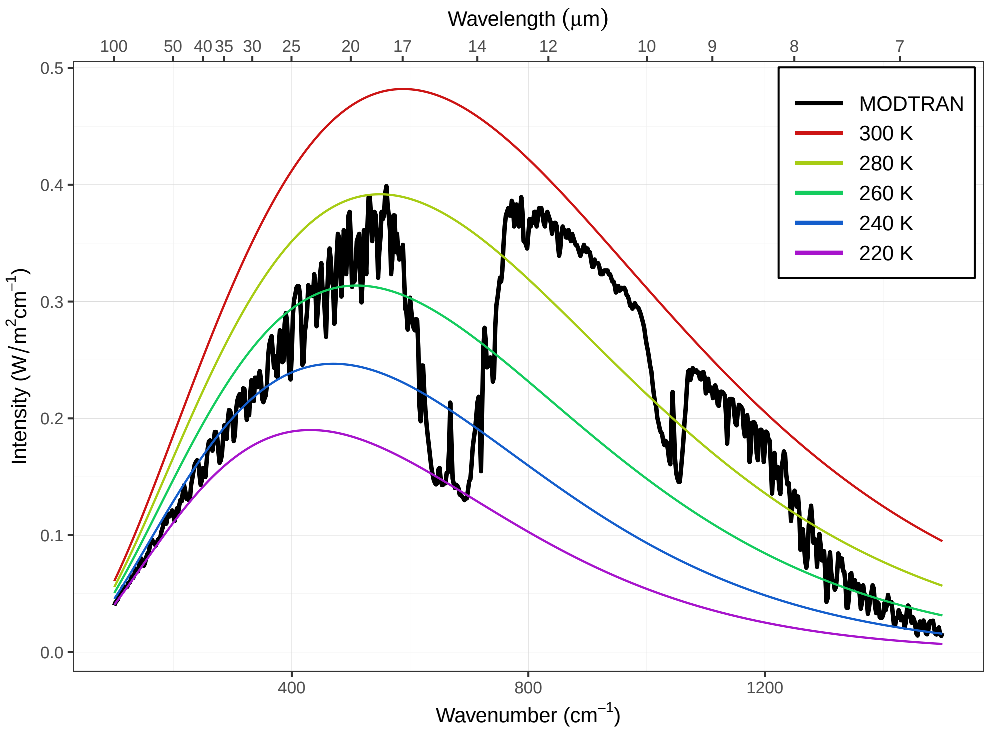
(a) Why does the CO_3^{-2} ion concentration drop?

(b) Why does the rate of carbonate burial drop? How does the decrease of carbonate burial affect the CO_3^{-2} concentration?

(c) How do these changes affect the amount of CO_2 in the atmosphere, and what are the implications for the fate of CO_2 emitted by burning fossil fuels?

3. We worry about carbon dioxide, methane, nitrous oxide, and many other greenhouse gases, but not water vapor. Water vapor is a very powerful greenhouse gas and is responsible for around three quarters of the natural greenhouse effect. Why don't we worry about water vapor emissions contributing to global warming?

4. In the figure below, the black line shows the intensity of infrared light at different wavelengths, as measured by a satellite looking down at the earth. The earth's surface temperature is 280K. The colored lines show the emission from ideal black bodies at different temperatures from 220Kto 300K.

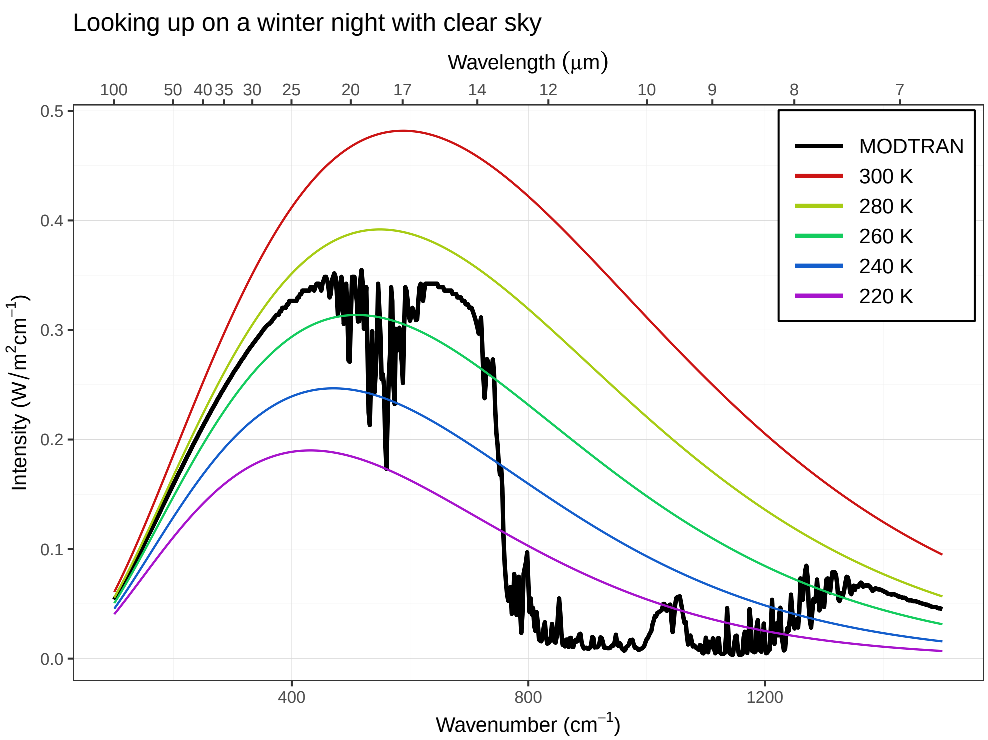


(a) Identify the regions of the spectrum where water vapor and CO_2 absorb strongly.

(b) Briefly explain why the radiation from 800–1000 wavenumbers (cycles/cm) is close to the 280K blackbody curve, but the radiation around 650–700 wavenumbers and 1300–1500 wavenumbers is close to the 220K and 260K blackbody curves, respectively.

(c) What do your answers to the previous part tell you about the skin height for CO_2 versus water vapor?

5. In the figure below, the black line shows the intensity of infrared light at different wavelengths, as measured by a satellite looking up from the earth's surface on a clear winter night, where the ground temperature is 272K. The colored lines show the emission from ideal black bodies at different temperatures from 220K to 300K.



(a) What blackbody temperature corresponds roughly to the intensity of radiation at the wavenumbers where CO_2 absorbs strongly?

(b) Briefly explain why the radiation from 800–1000 wavenumbers (cycles/cm) has such low intensity (far below the 220K blackbody curve), but the radiation around 700 wavenumbers has much greater intensity.

(c) Roughly sketch on the diagram what the emission would look like if the sky were completely covered with low-lying stratus clouds.

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Answer Key for Practice Midterm Exam

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    $\boxed{\text{(d)}}$ (a) and (b)

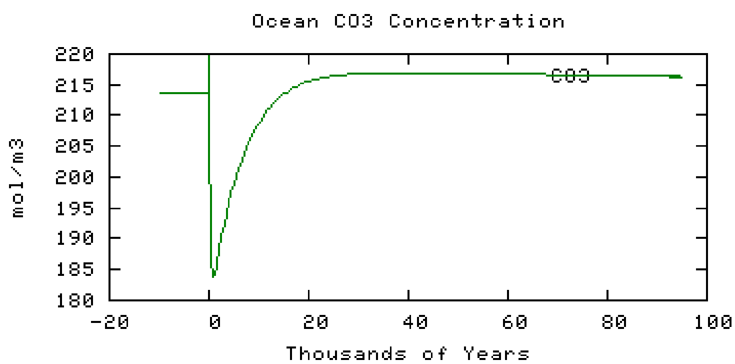
    (e) All of the above.

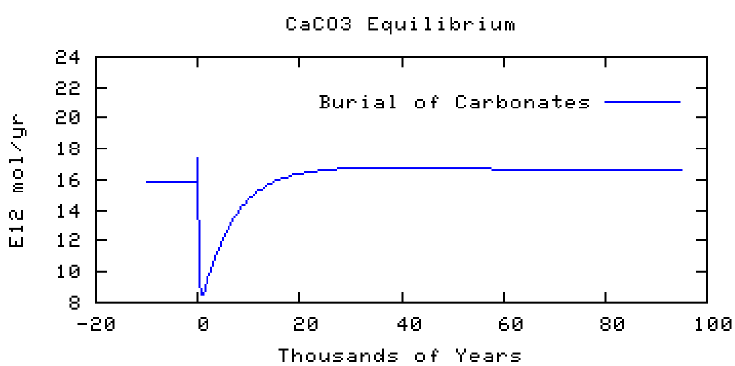
Section 2. Free-response questions (60 points total).

1. Consider the ice-albedo feedback:
   (a) How does it work?
   (b) Is it positive or negative?
   (c) Did this feedback play an important role in the Pleistocene ice ages?

Answer: *(a) As temperatures get colder, more ice and snow cover the earth's surface. This increases the albedo (reflects more sunlight), which causes further cooling. As temperatures get warmer, less ice and snow cover the surface, so albedo drops and temperatures rise further.*
(b) This feedback is positive.
(c) Albedo feedback was responsible for a large fraction of the temperature changes during the ice ages (roughly half, although you don't need to know this detail).

2. The figures below show changes in both the concentration of CO_3^{-2} ions in sea water and the rate at which carbonate minerals (mostly shells of tiny plankton organisms) are buried in sediments on the sea floor after a big pulse of CO_2 is released into the atmosphere.





Briefly describe:

(a) Why does the CO_3^{-2} ion concentration drop?

Answer: *When CO_2 dissolves into the water, it reacts with CO_3^{-2} to form bicarbonate (HCO_3^-) ions. The more CO_2 dissolves, the more CO_3^{-2} is consumed.*

(b) Why does the rate of carbonate burial drop? How does the decrease of carbonate burial affect the CO_3^{-2} concentration?

Answer: *As the ratio of bicarbonate (HCO_3^-) to carbonate (CO_3^{-2}) ions increases, the ocean becomes more acidic. This causes carbonate minerals, such as $CaCO_3$ in the shells of tiny plankton, to dissolve in the seawater before they can be buried on the sea-floor. As these minerals dissolve, the replenish the CO_3^{-2} concentration somewhat.*

(c) How do these changes affect the amount of CO_2 in the atmosphere, and what are the implications for the fate of CO_2 emitted by burning fossil fuels?

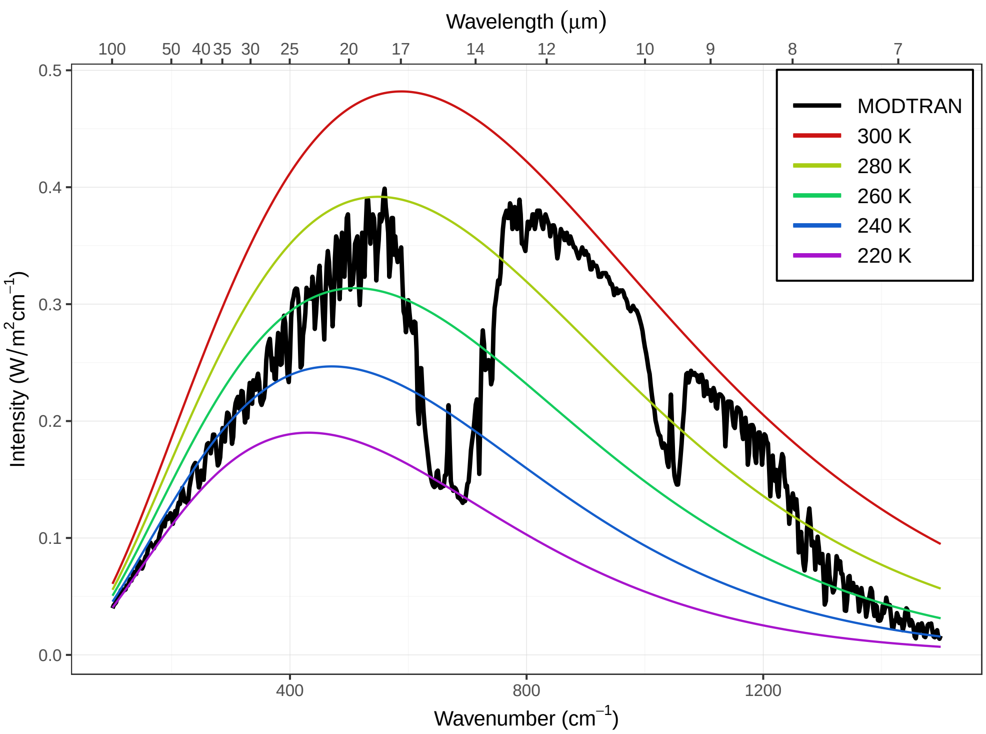
Answer: *As the CO_3^{-2} concentration drops, the oceans become saturated with CO_2 and can absorb new CO_2 only as fast as dissolving carbonate minerals adds new CO_3^{-2} ions. This means that the greater the amount of CO_2 in the atmosphere, the slower the oceans can remove it, so the more fossil fuels we burn, the longer the resulting CO_2 will stay in the atmosphere.*

3. We worry about carbon dioxide, methane, nitrous oxide, and many other greenhouse gases, but not water vapor. Water vapor is a very powerful greenhouse gas and is responsible for around three quarters of the natural greenhouse effect. Why don't we worry about water vapor emissions contributing to global warming?

Answer: *Water vapor is different from all the other greenhouse gases for two reasons:*

- *It has a very short residence time in the atmosphere: the average water molecule only remains in the atmosphere for around 10 days, so water vapor can't build up over time the way other greenhouse gases can, which have lifetimes of decades or centuries.*
- *The concentration of water vapor in the atmosphere is close to equilibrium, as controlled by the temperature, so the water vapor responds to other things that change the temperature, but due to its short lifetime, it doesn't initiate temperature changes.*

4. In the figure below, the black line shows the intensity of infrared light at different wavelengths, as measured by a satellite looking down at the earth. The earth's surface temperature is 280K. The colored lines show the emission from ideal black bodies at different temperatures from 220Kto 300K.

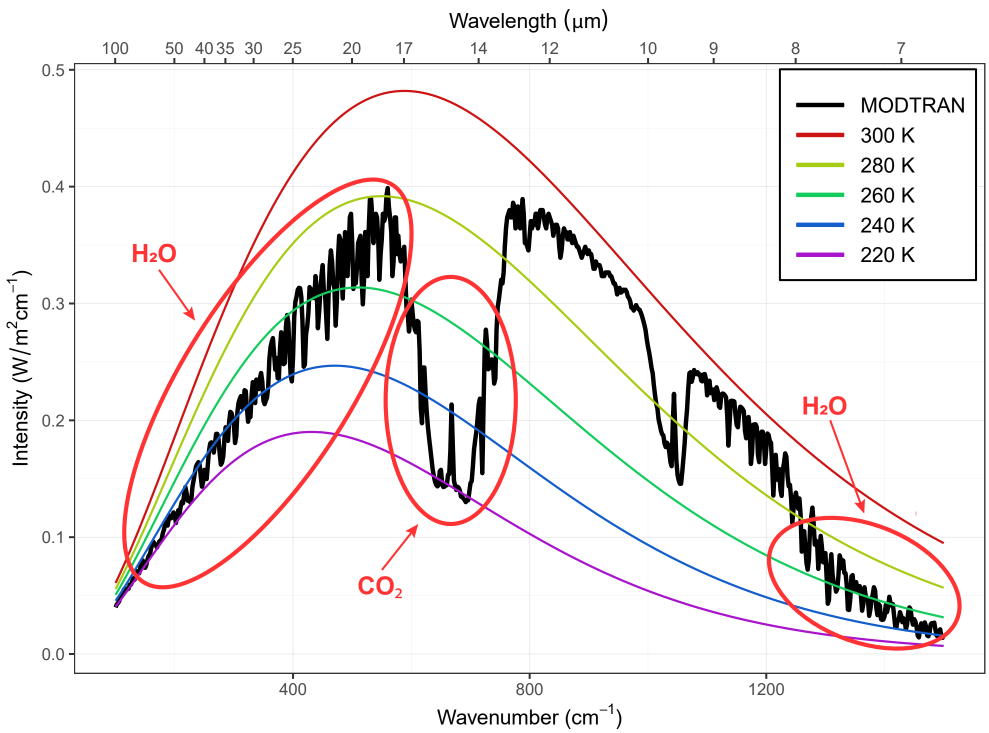


(a) Identify the regions of the spectrum where water vapor and CO_2 absorb strongly.

(b) Briefly explain why the radiation from 800–1000 wavenumbers (cycles/cm) is close to the 280K blackbody curve, but the radiation around 650–700 wavenumbers and 1300–1500 wavenumbers is close to the 220K and 260K blackbody curves, respectively.

(c) What do your answers to the previous part tell you about the skin height for CO_2 versus water vapor?

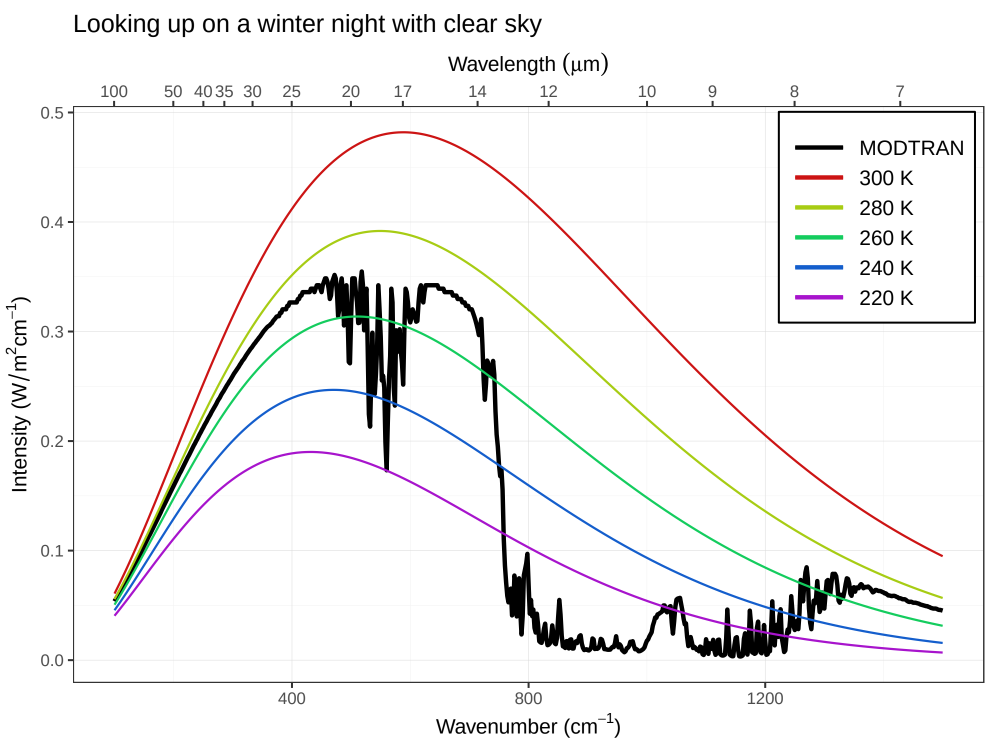
Answer: *(a) See the figure below.*



(b) Where the absorption is greater, due to greenhouse gases, only radiation emitted higher in the atmosphere (at the skin height) can pass through the remaining air overhead to be seen by a satellite. The atmosphere cools off as you go up, so the higher the skin, the colder the temperature, and the weaker the radiation. So regions of the spectrum that follow colder blackbody curves correspond to regions where the skin is higher, which means that something in the atmosphere absorbs strongly in that region of the spectrum.

(c) CO_2 radiates with the coldest temperature, so it has the highest skin height. Water vapor has warmer temperatures, and hence a lower skin height. (It's not part of this question, but the region 800–1000 has a skin height that's very close to the ground, with a spectrum that's very close to the 280K ground temperature.

5. In the figure below, the black line shows the intensity of infrared light at different wavelengths, as measured by a satellite looking up from the earth's surface on a clear winter night, where the ground temperature is 272K. The colored lines show the emission from ideal black bodies at different temperatures from 220K to 300K.



(a) What blackbody temperature corresponds roughly to the intensity of radiation at the wavenumbers where CO_2 absorbs strongly?

(b) Briefly explain why the radiation from 800–1000 wavenumbers (cycles/cm) has such low intensity (far below the 220K blackbody curve), but the radiation around 700 wavenumbers has much greater intensity.

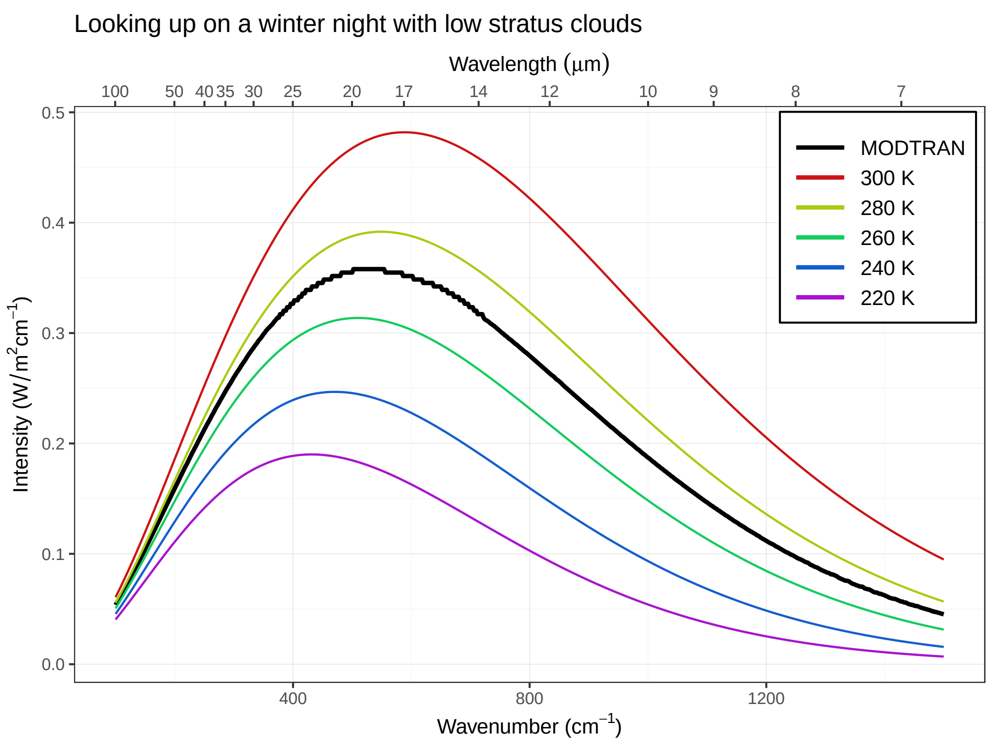
(c) Roughly sketch on the diagram what the emission would look like if the sky were completely covered with low-lying stratus clouds.

ANSWER: *(a) The emission is between the 260K and 280K blackbody curves, so somewhere around 270K. Anywhere from 265-275K would be a reasonable guess that would get full credit, and a better guess would note that the ground temperature is 272K and the emission from CO_2 would be close to this.*

(b) The part of the spectrum from 800–1000 wavenumbers corresponds to the atmospheric window, where the atmosphere is transparent to longwave radiation (and thus, the emissivity ε is close to zero). Since ε is so small throughout the atmosphere, blackbody radiation from the atmosphere at these wavelengths is very dim and there is no warm blackbody to produce radiation in this range.

Near 700 wavenumbers, on the other hand, CO_2 absorbs strongly, so its ε is close to 1. This means the warm layers of the atmosphere near the surface emit like perfect blackbodies at this wavenumber and the intensity of the radiation is close to a blackbody at the ground temperature (272K).

(c) See the diagram below.



Clouds radiate like blackbodies, so a sensor looking up would see radiation like a blackbody with the temperature of the bottom of the cloud. Since stratus clouds are very low, that temperature will be close to the ground temperature.